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HIGH-POWER TESTING OF 30 GHZ ACCELERATING STRUCTURES AT THE CLIC TEST FACILITY (CTF II)

H. H. Braun, S. Döbert, L. Groening, I. Wilson, W. Wuensch, F. Zhou

Abstract

During the year 2000, experiments using the CLIC Test Facility [1] (CTF II) focused on high-power testing of 30 GHz CLIC prototype accelerating structures [2] (CAS) and on investigating the processes involved in RF breakdown. For this purpose, a 30 GHz high-power test stand equipped with diagnostics for breakdown studies has been developed. The experimental set-up, diagnostics and performance of the one meter long power extraction structure used to feed the accelerating structures with 30 GHz power will be described. A single-feed coupler CAS assembled by AEG, a planar structure produced by the University of Berlin, and a double-feed coupler CAS made at CERN, were tested in CTF. The accelerating and surface gradient limits found for these structures at different RF pulse lengths, and ideas about the processes involved in electrical breakdown, are summarised and discussed.

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ABSTRACT

During the year 2000, experiments using the CLIC Test Facility [1] (CTF II) focused on high-power testing of 30 GHz CLIC prototype accelerating structures [2] (CAS) and on investigating the processes involved in RF breakdown. For this purpose, a 30 GHz high-power test stand equipped with diagnostics for breakdown studies has been developed. The experimental set-up, diagnostics and performance of the one meter long power extraction structure used to feed the accelerating structures with 30 GHz power will be described. A single-feed coupler CAS assembled by AEG, a planar structure produced by the University of Berlin, and a double-feed coupler CAS made at CERN, were tested in CTF. The accelerating and surface gradient limits found for these structures at different RF pulse lengths, and ideas about the processes involved in electrical breakdown, are summarised and discussed.

1. INTRODUCTION

One of the objectives of the CLIC Test Facility was to demonstrate two-beam acceleration in a series of CLIC [3] prototype modules. The facility consists of an S-band drive beam linac which produces a bunched high-charge beam capable of producing 30 GHz RF power, and a low-charge S-band probe beam linac to probe the accelerating fields achieved in the 30 GHz accelerating sections. In 2000, the two-beam acceleration modules were removed and a high-power test stand configuration was installed, consisting of a single decelerating structure feeding a test area in the probe beam linac (see fig. 1).

The drive beam linac can accelerate 12, 24 or 48 bunches of a total charge of more than 500 nC to about 40 MeV. A magnetic bunch compressor chicane compresses the bunches to a bunch length of ~5 ps which is needed for efficient 30 GHz power production in the one meter long power extraction structure [4]. This configuration enables production of 30 GHz RF pulses with lengths of 3, 7 and 15 ns to test the prototype accelerating structures. The accelerating fields produced in the 30 GHz accelerating structures are probed with a single 500 pC probe beam electron bunch by measuring energy gain in a downstream spectrometer.

2. TEST STAND DIAGNOSTICS

Most of the diagnostics used in the high gradient experiments was developed over the course of the year and as result of accumulating experience. The diagnostics developed for the structure test stand has to cope with very short RF pulse lengths and with a high radiation environment associated with the losses of the high-charge drive beam. The incident, reflected and transmitted power waveforms were measured by down-mixing to an intermediate frequency of 500 MHz using a phase-locked reference signal and digitisation on a fast oscilloscope. Better time resolution, but without phase information, was later obtained by a 1 GHz IF-electronic system.

One of the most sensitive indicators of an RF breakdown event is an electron burst measurable at the upstream and the down-stream end of the structure. This current emission is measured with two pairs of wall-current monitors (WCM) at each end of the structure.

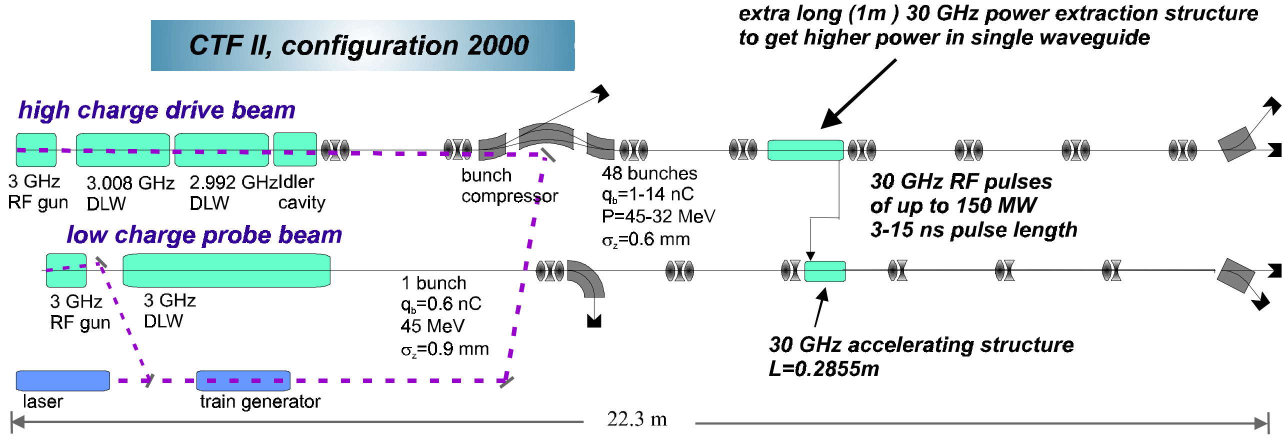

Figure 1: Configuration of CTF II in the year 2000 as a 30 GHz high-power test stand.

The WCM's of each pair are separated by about one meter to allow an energy determination of the breakdown electrons via a time of flight measurement. A solenoid guides the low-energy electrons over this distance.
Vacuum gauges determine the pressure in the section, in the input and output waveguides, and in the beam pipes.
A fast X-ray detector consisting of a BaF_2 crystal and a fast photo multiplier tube (PMT) was used to measure X-rays emitted during the breakdown events. Unfortunately, due to the background from the nearby high-charge drive beam, a discrimination of breakdown events was impossible.
An acoustic sensor was used to detect shock waves associated with electrical breakdown. The amplitude of the acoustic signal was well correlated with breakdown events. The location of a breakdown in the section could be detected with such sensors because they detect thermal shock wave initiated at the breakdown location [5].
An upstream aluminium screen was used as a mirror to observe visible light emitted along the beam pipe associated with a breakdown event. This light could be detected with a PMT, which is sensitive in the wavelength range between 300-650 nm.

3. THE POWER EXTRACTION STRUCTURE

A one meter long prototype CLIC transfer structure (CTS) was used for 30 GHz power production. The transfer structure performed very well at different pulse lengths. The output power was only restricted by the amount of power, which could be fed into the accelerating structures. The power limits at 15, 7 and 3 ns pulse length from the CAS due to breakdowns were 40, 80 and 160 MW respectively.
The transmission through the CTS structure was typically better than 90 %. In order to increase beam transmission even further, a solenoid was installed around the middle 50 cm of the structure. The solenoid slightly improved the transmission, but a pressure rise was observed. In addition shortening of the CTS output pulse was observed at a pulse length of 15 ns. This effect was not observable at shorter pulse lengths. It will be investigated if this observations could be explained by a multipactor threshold.
After the run in 2000, the CTS was inspected with an optical endoscope and a few teeth were found to be damaged in the region of very high electric fields near the output coupler. Simulations with HFSS [7] indicated surface gradients in the damaged region reaching 220 MV/m for 160 MW output power.

4. HIGH-POWER TEST RESULTS

A typical breakdown event in one of the CAS structures shows the following features:

- Strong electron currents are emitted during the RF pulse. The upstream current signal, which was always much higher than the downstream signal, can reach a peak current of several hundred mA. The energy of these electrons is in the range of 10-70 keV and shows some dependence on the accelerating gradient in the structure.
- Visible light is emitted during a breakdown, lasting up to one microsecond after the RF pulse, showing a sort of 'afterglow' phenomenon (see fig.2).

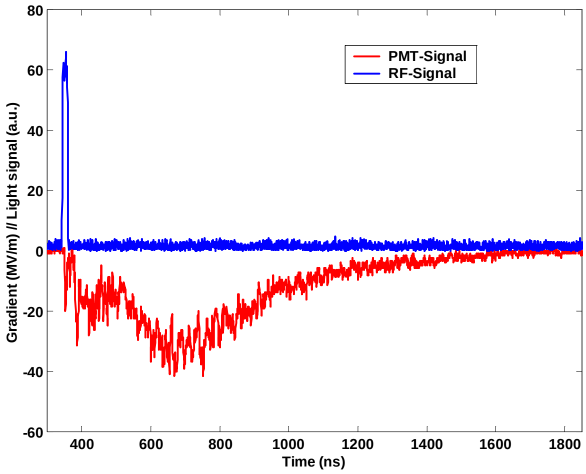

Figure 2: Visible light emission after a breakdown.

The total amount of emitted light is correlated with the amount of missing energy in a breakdown event and the temporal maxima of emission are later for longer RF pulse lengths. This light emission can be interpreted as evidence of a plasma formed during a breakdown, which lasts much longer than the RF pulse. This interpretation is confirmed by the observation of the attenuation of low-power RF waves caused by reflection from the output load which travel through the structure after the initial RF-pulse has gone.

- A pressure rise in the cavity can be observed. Vacuum activity is strongest at the beginning of the conditioning but decreases as the processing continues.
- The RF power transmission shows pulse shortening during breakdown but, in contrast to observations made by other groups [6], full reflections are never observed. The missing energy for a breakdown event calculated from the RF signals (missing energy = incident-transmission-reflection) can be up to 50 %, while the reflection changes only by a few percent.

Three different 30 GHz accelerating structures were high-power tested in CTF II during the year 2000. Two of them were made out of high-precision diamond-turned disks with an optical-quality surface finish, joined using a hybrid defusion-bounding / brazing technique. This technology was developed at CERN. One of these 30 cm long CLIC prototype structures was equipped with single-feed input and output couplers and assembled at AEG. This structure was already used with moderate power levels in the test facility for the two-beam acceleration experiments. The second structure (DF-Section) was the first prototype equipped with double-feed input and output couplers to improve the asymmetric field configuration in the coupler cell, and it was built at CERN.

The third cavity tested was a planar structure [8] using a muffin-tin geometry built by a collaboration between the University of Technology in Berlin and DULY Research, US. The 12 cm long cavity was machined by high-precision milling using classical tools, and it was brazed at CERN. The surface finish of this cavity was clearly poorer than the diamond-machined ones. The objective of the planar structure concept, beside being a prototype for a linear collider accelerating structure, is to try alternative accelerating structure geometries suitable for new fabrication techniques, especially at very high frequencies, even beyond 30 GHz.

A summary of the accelerating and surface gradients obtained after high-power conditioning is found in table 1.

Structure	***E_{acc} \ $E_{surface}$ (MV/M)***		
pulse length (ns)	**3**	**7**	**15**
AEG, LH side	**133 \ 588**	**90 \ 398**	**59 \ 260**
AEG, RH side	**140 \ 619**	**100 \ 442**	**60 \ 265**
Planar Structure	**95 \ 570**	**60 \ 360**	**50 \ 300**
DF-Section	**120 \ 456**	**95 \ 361**	**70 \ 266**

Table 1: Gradient limitations found for the various structures tested for different pulse lengths.

The maximal gradients quoted above at different pulse lengths represent the performance after typically less than a million RF pulses. An 'ultimate' RF processing of this type of structure has not been done yet because of the low repetition rate of CTF II (5 Hz), but it may result in somewhat higher gradients.

In addition more qualitative results were obtained during the high-power experiments. The AEG-structure was used as a test object to develop the diagnostics and was also tested under various vacuum conditions. Between the AEG-LH and RH runs the vacuum level was improved from 10^{-5} mbar to at least 10^{-8} mbar and an in-situ bake-out to 120 ^{o}C was performed to reduce the outgasing. No clear evidence was found that improving the vacuum, and carrying out a low-temperature in situ bake-out is advantageous for high gradients. The lower base pressure results in a much stronger and sensitive response of the gauge readings to a breakdown event.

The iris of the input coupler cell (RH-side) of the AEG-structure was found to be damaged after testing up to an accelerating gradient of 140 MV/m at 3 ns and 60 MV/m at 15 ns. Once the diagnostic set-up and the bake-out procedure was fixed, the structure was turned around to test the undamaged output coupler side (LH-side). After some conditioning, approximately the same performance was achieved and an optical inspection revealed identical damage patterns (see fig.3). The damage pattern is asymmetric on the first iris of the structure and corresponds very well with the local surface gradient (see fig.4) and power flow distributions [9]. The second iris appears to be symmetrically pitted

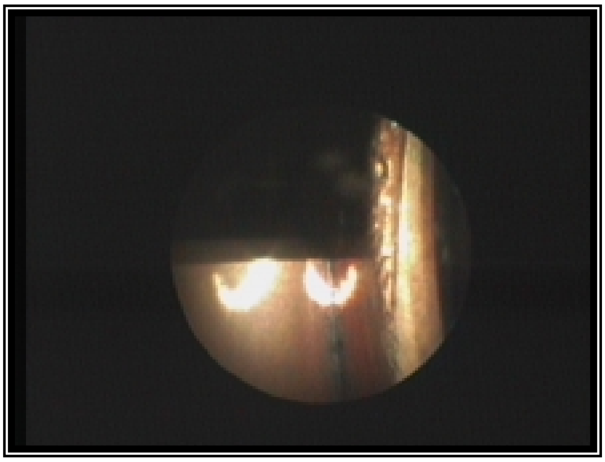

Figure 3: Damaged coupler iris, looking from the beam axis towards the coupling aperture. The section continues to the right.

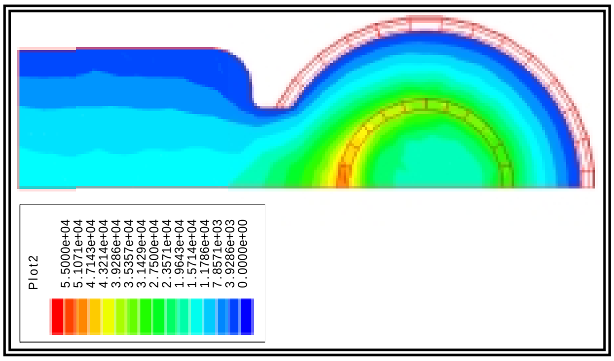

Figure 4:Simulation of the surface field distribution on the coupler iris using HFSS. The input waveguide comes from the left and the figure shows the first iris towards the disk-loaded waveguide.

but there are no large amounts of missing material as on the first iris. The surface field enhancement on the upper half of the first iris due to the single-feed coupler amounts to 40 %. For the structure with the double-feed coupler (DF-Section), the field enhancement is about 20 %. It turned out that this structure showed similar limitations in terms of surface gradient at a pulse length of 15 ns, but performed somewhat less well at very short pulses. Inspection after conditioning showed a symmetric damage pattern, which was again well correlated with the surface gradient distribution. Even the 'damaged' structure showed no degradation of the electron accelerating ability. The planar structure appears also to be damaged in the high surface field regions on the irises. The values for the surface gradient quoted for this cavity in table 1 are only roughly estimated because of a lack of precise geometrical data. The surface gradient is not only correlated with the resulting damage but seems to play an import role also in initiating breakdown events.

The accelerating gradient is well correlated with the number of electrons emitted and the missing energy in a breakdown event (see fig.5).

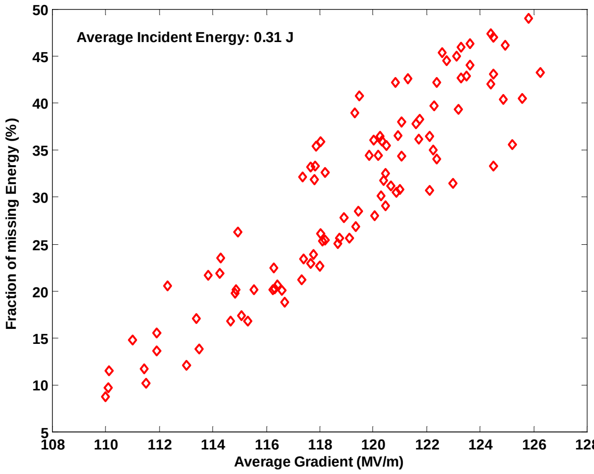

Figure 5: Correlation between missing energy and average accelerating gradient.

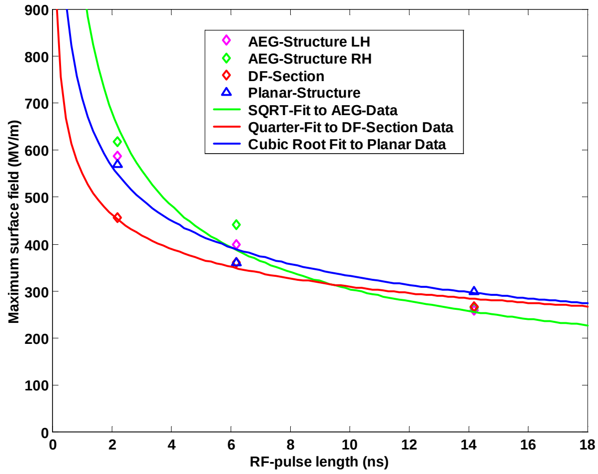

Figure 6: Measured pulse length dependence for the different structures tested .

The wall-current monitors were also used to observe the emitted dark current, which starts at accelerating gradients of about 95 MV/m. A Fowler-Nordheim analysis [10] of the dark current measurements resulted in an estimate of the field enhancement factor due to surface roughness and protrusions. The enhancement factors for the diamond-machined cavities were found to be rather low, between 20 and 30. Multiplying the measured field enhancement factors by the observed surface field limits, results in effective surface fields (~10 GV/m) corresponding to a Fowler-Nordheim current sufficient for melting emitters.

5. DISCUSSION AND OPEN QUESTIONS

The breakdown phenomena observed during high-power tests of 30 GHz accelerating structures show severe limitations in terms of the achievable accelerating gradient. The CLIC parameters aim for an average accelerating gradient of 150 MV/m at a pulse length of 130 ns. So far, an accelerating gradient of 70 MV/m has been demonstrated but at a pulse length of 15 ns and with damage in the input coupler region. It is not known if the damage would continue with further conditioning and/or high gradient operation.

The pulse length dependence of the breakdown gradient is summarised in fig.6 for the three structures discussed.

The surface gradient limitation, especially at longer pulse lengths seems to be independent of the structure geometry and there seems to be no general law to describe the dependence. The popular square root dependence that implies constant energy as a critical parameter (see for example [6]), fits the AEG data best. DF-Section is best fitted by a fourth root law, which would be consistent with a dependence found empirically for the limitations by explosive field emission in the regime of short dc pulses [11]. The limit is given by the local melting of copper, due to ohmic losses at the location of a field emitter. The cubic root dependence found for the planar structure has no well-defined physical interpretation to the author's knowledge.

Most of the results presented above imply that the maximal surface gradient plays a limiting role and that we are reaching a physical limit for copper using our present surface preparation techniques. The CLIC approach to solving the breakdown problem consists first of reducing the ratio of $E_{surface}/E_{acc}$ by modifying the geometry of the structure, secondly by investigating alternative materials to copper, and thirdly implementing cleaner surface preparation techniques. A short prototype accelerating structure aiming for a ratio of $E_{surface}/E_{acc} \approx 2$ is currently prepared as well as a structure using a tungsten iris in the input coupler. Tungsten was chosen because it is well known for its spark-resistance. The influence of different surface preparations should be investigated with respect to peak field performance, as well as the pulse length dependence. Surface preparation could include clean-room handling and assembly, high-pressure water rinsing, coatings, Argon-glow-discharge and electropolishing.

A better understanding of the breakdown mechanisms and damage mechanisms, which are not necessarily the same, would help to orient the study. So far we know that the breakdowns happen very fast (a typical time scale is 10 ns) and, that electrons play an important role in initiating and maintaining the breakdown. Some sort of plasma is created, which lasts much longer than the RF pulse. It is not known if the plasma is a result of an explosive event (bulk copper or particle) or liberated gas due to electron impact The origin of the electrons involved is also not clear, they could come from field emission, from the plasma or from secondary emission. What seems most sure is that electrons seem to initiate the breakdown process.

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